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Valid knowledge for the professional design of large and complex design processes

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The organization and planning of design processes, which we may regard as design-process design, is an important issue. Especially for large and complex design-processes traditional approaches to process design may no longer suffice. The design literature gives quite some design process models. As prescriptive knowledge these models may support a more professional approach to process design. However their impact on the practice of process design is still too limited. The reasons for this may include that the potential of professional process design to produce effective and efficient design processes is still underestimated as well as the potential of prescriptive design knowledge to support that professional process design. In this article I intend to contribute to a better understanding of these potentials by analysing the nature of prescriptive design knowledge, the way it can be used to produce sound design processes and an approach to develop prescriptive process-design knowledge. I will describe prescriptive design knowledge in terms of field-tested and grounded solution concepts and the impact of their application on actual design processes through a dual redesign process. And I will discuss the multiple case-study as an approach to develop field-tested and grounded solution concepts.

key words: design processes, design knowledge, design research

Both in architectural design and in engineering design the organization and planning of design processes is an important issue, especially of large and complex ones. One may regard this organizing and planning as design-process design. However, in practice one tends to use fairly traditional approaches to process design. If a specific and formal process-design is made at all, it usually is a copy or limited adaptation of a previously used one[1]. This is unlike the usual more professional approach to object design, where the context of a new design assignment and the formal (and informal) specifications are thoroughly analysed and where the object-design is made on the basis of state-of-the-art descriptive and prescriptive design knowledge. As the scale of design processes increases, as well as their knowledge intensity and organizational complexity, traditional approaches to process design may no longer suffice. But for a more professional approach one needs evidence-based design knowledge. The design literature gives quite some process-design models and several of these may be used as prescriptive knowledge in process design. However, their impact on the practice of process design is still too limited. One of the reasons for this may be that in practice the potential of professional process design is underestimated and another that it has not been well articulated what the nature of prescriptive design knowledge is in the first place, and how such knowledge may be used in professional process design. In this conceptual article I will discuss prescriptive design knowledge in terms of field-tested and grounded solution concepts and the impact of the application of these solution concepts on the actual design process via a dual redesign process. Furthermore, I will discuss the multiple case-study as an approach to develop field-tested and grounded solution concepts.

This article has been developed on the basis of the literature and in the context of the two-year postgraduate course programme ADMS (Architectural Design Management Systems), established in 1997 at Eindhoven University of Technology. This course programme trains engineers to design large-scale complex design processes in the field of building and urban development. The graduation projects of the students of this course programme provided starting material for this article. My own field experience is more in innovation management. Combining these two backgrounds, this article does not have a specific orientation towards building projects but more a general orientation towards large and complex design projects.

1. Object, realization and process design

Design may be as old as modern man. Hand-held rock tools and primitive dwellings may have been designed, i.e. the makers of such artefacts may have reflected on the functions, materials, shapes and other aspects of the artefact to be made, before the actual physical work started. In ancient times artefacts were generally designed by their makers themselves. Over time designing has been separated from making, allowing for a more professional approach to design, especially since the Industrial Revolution. This applies in particular to object design, to a somewhat lesser extent to realization design (i.e. the design of the realization process, the physical process through which the artefact has to be built on assembled) and even less to design-process design.

1.1. object design

Important artefacts like farmhouses, farm carts, ships, the scythe and the violin have been developed over time through a process of *evolutionary design* (Jones, 1980; French, 1994). Designs were passed on from generation to generation, verbally on implicitly via realized designs and incorporating from time to time some incremental improvement. Evolutionary design is design according to the traditions of the trade in question.

A radical improvement in designing was the separation of the designing of an artefact from its realisation. The designer made some representation of the artefact to be made, usually in the form of drawings, and passed that representation, the *object-design*, on to others – like a workshop, a contractor – to realize the design. This allowed a professionalization of object design through the training and specialization of designers and through the development of object knowledge, knowledge on the properties and behaviour of artefacts. The enormous technological progress, especially since the Industrial Revolution is driven by this accumulation of object knowledge, both by the natural and by the engineering sciences and by the training of professional designers to use this object knowledge, i.e. in this case engineers.

These developments caused an emancipation of object design from the evolutionary design mode. Evolutionary design implies that a new design is largely copied from previous ones, thus incorporating numerous *implicit design decisions,* choices made by previous generations of designers. Professional designing is playing with alternatives. “Don’t marry your first design idea” (as Dym says; Dym, 1994, p26), but experiment (on paper) with the various solution concepts which may be used for your design problem. Making conscious design decisions leads to better designs as the impressive technological developments of the last centuries show.

So, professional design made more radical object-designs possible and these were indeed made. Nevertheless, most object design is *variant design*, i.e. the new design is an adaptation of one or more already existing specific object-designs or already available general solution concepts that are used as a *design exemplars* for the new design. A *really* radical innovation departs from variant design, does not resemble previous designs, but in most cases the distinction between radical and incremental design is a matter of degree: to what extent does the new object-design differ from the design exemplars. Still, professional variant design is very different from evolutionary design, even if it is only incremental design. As said above, in professional design the design assignment (context and specification) is thoroughly analysed and the new design is made using state-of- the-art knowledge. In evolutionary design the design exemplar with its implicit design decisions is largely copied, while only a limited adaptation is made on the basis of some desired improvement

1.2 realization design

The process of creating artefacts is driven by two essentially different human action systems: one producing designs and one producing the artefacts on the basis of those designs. The first operates in the essentially immaterial world of knowledge, texts, drawings and the like, and the second in the material world of physical processes, producing physical artefacts.

So, after the object-design has been made, the artefact in question has to be realized through a physical process, like a building or a production process. Often that process is already present in one form or another, be it a traditional one that can be copied without much effort for the new artefact, like is often the case in building, or already present as the production process (with its equipment and trained workers) of a factory. That realization process may be the result of evolutionary design, but nowadays can also be the result of an explicit *realization design*, a formal design of the realization process. Such a realization design is often made as a variant of an already existing building or production process, that is used as a design exemplar. Of course, also in professional realization design, one does not make for every new object-design a new realization design. Often an adequate realization process is already available and does not need to be redesigned for the new artefact.

Usually the people realizing the object-design have a certain, but usually limited *realization freedom*, i.e. the object-design does not specify each and every detail of the entity to be realized. For instance, a design of a bridge may not specify the type of rivets to be used, leaving it to the contractor to decide on this. As we will see in section 4.4 a fundamental difference between object design and process design is that in the latter case the people realizing the design get and take much more realization freedom than in the case of object design. Among other things this results in the fact that the process designer has much less control over the realization of his/her design than the object designer has.

1.3 process design

To produce an object-design and, as far as necessary, a realization design, one may want to design the design process itself, see fig. 1. However, like in the case of the realization process, in many cases already some kind of design process may be in place. Experienced individual architectural or engineering designers, or small teams of them, tend to use informal procedures for their design processes, which they have developed over time through their initial professional training and through subsequent experimenting and learning. Neither do large and experienced design and development organizations, like architectural firms or high-tech industrial companies, produce as a rule each time complete

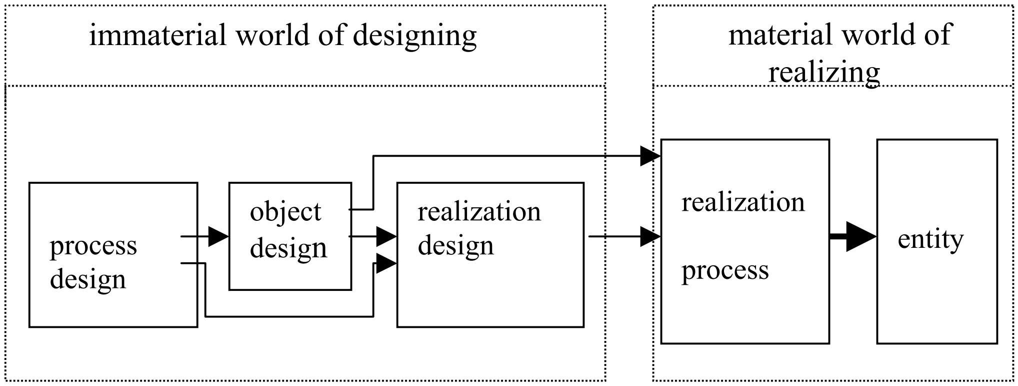

Fig.1 Process, object and realization design

redesigns for their design processes when starting a new design project. Like the experienced individual designers they also tend to use their customary set-up for their design process, which they have developed over time through experimenting and learning, possibly somewhat adapted, if the new design project seems to differ from previous ones. This approach to process design can also be seen as a kind of evolutionary design of the discipline in question: approaches to design processes are passed on from generation to generation, verbally and implicitly by having young designers copy the approaches of their teachers in a way, comparable to the master-journeyman teaching mode of medieval guilds. Professionalization of process design has much less progressed than in the case of object and realization design. As we will see this may be related to the fact that in object and realization design one designs respectively material objects and processes with strong material elements, while in process design one designs human action systems, having a fundamental different nature.

2. Process design literature

Developing knowledge to support professional design processes is one of the key objectives of (academic) design research. The literature on design process gives both descriptive and prescriptive process designs.

2.1 design process models

The design literature has produced a great variety of models of design processes, including the following list, wherein I mention the author and the principal elements of the model. A major source for this list was the review paper by Evbuomwan, Sivaloganathan and Jebb (1996).

a. *Marples* (1960): designing is a sequence of decisions, starting from the original statement of (functional) requirements and ending by the (technical) specifications of the artefact to be produced. These decisions are represented in a “Marple tree”, with the functional specification as starting mode and then branching out via subsequent levels of sub-decisions.
b. *Asimow* (1962): feasibility study phase, preliminary design phase, detailed design phase.
c. *Watts* (1966): cycles of analysis, synthesis and evaluation, moving through design decisions from abstract levels to ever more concrete ones.
d. *Archer* (1971): six stages, viz. programming, data collection, analysis, synthesis, development, communication, with iterations between the stages where necessary.
e. *French* (1971): analysis, conceptual design, development of the generated schemes, detailing
f. *Jones* (1980): three stages, viz. analysis, synthesis and evaluation
g. *Pahl and Beitz* (1984, original German version 1971): clarification of the task, conceptual design, embodiment design and detail design.
h. *VDI 2221* (1987), a model produced by the German association of engineers: clarification and definition of the design task, determination of the required functions, search for solution principles for all sub-functions and combination into principal solutions, division of solution into principal modules, development of key modules into a set of preliminary layouts, development of definitive layouts and final documentation.
i. *Cross (1991)*: six stages, three decomposing the overall problem into sub problems, viz. clarifying objectives, establishing functions, setting requirements, and three stages synthesizing the overall solution, viz. generating alternatives, evaluating alternatives, improving details.
j. *Roozenburg and Eekels* (1995, original Dutch version 1991): four basic steps, viz. analysis, synthesis (of the solution to the design problem), simulation (prediction of the properties of the new artefact), evaluation (overall assessment), with possible iterations between the steps.
k. *Reymen (*2001): organize the overall design process in a sequence of design sessions, each starting with planning and ending with reflection.

Furthermore, the innovation management literature provides design process models, like

l. *Cooper* (1990): the so-called stage-gate process, wherein the overall design process is subdivided into a number of stages, each stage to be concluded with a “gate”, where an in-depth review process is used to decide whether or not the design project may proceed to the next stage
m. *Cooper* (1994): an improved stage-gate process with fluid stages and fuzzy gates
n. *Prasad* (1997): one of the many books discussing *concurrent engineering*, an approach where realization design is not done after object design but concurrently.

2.2 reflection

So the design literature gives quite some design process models. However, their impact on the practice of design is, unfortunately, as yet still too limited. As Schregenberger says “A few former researchers are applying their advanced knowledge successfully on the job. Apart from that, practice is still waiting for new impulses” (Schregenberger, 1998, p59). See further e.g. Dorst, 1997, Van Handenhove and Trassaert, 1999, and Andreasen, 2001.

Reflection on the process model literature leads to a number of questions, including the following three. The first one concerns the basis on which the model has been developed. Some models are based on a synthesis of case-studies, like the model of Marples, others are based on the experience of prominent designers, like the VDI 2221 model (Pahl,1998). For several models their empirical basis is unclear. They seem to be based on the authors own experience and clear thinking, and inspired by the design literature. That is a respectable basis, especially in a design environment as many good designs are made in that way. Still, one might want some more justification of a design model.

Another issue is the nature of the models in question. The difference between descriptive and prescriptive models is often unclear. Dym, for instance, discusses in section 3.2 two descriptive process models and opens section 3.3 with: “We now present two prescriptive models of the design process. These models differ from the two descriptions given in Section 3.2 in that they *prescribe* a set of tasks that must be completed in order to generate a satisfactory design” (Dym, 1994, p 28; italics in original). But the two models of section 3.2 and the two of 3.3 have a quite similar nature, although the prescriptive ones are somewhat more detailed. The major difference might be the intentions of their makers. In their review Evbuomwan et al. write “design models are the representations of philosophies or strategies proposed to show how design is and may be done”. (Eubuomwan et al. 1996, p305). In this quote description (“how design is”) and prescription (“how design may be done”) are neatly fused. Like in the first quote this is understandable: an analysis and description of a successful design process may be used as a prescription: “use this process and you will equally be successful”. However, there is more to prescription than this. If company A copies a design process, that was successful in company B, would it also be as successful in their company? There certainly will be differences in the context and nature of the design projects of the two companies; to what extent should they warrant differences in their process-designs?

And then there is the question of what “successful” is in the first place. What are the performance indicators for judging the success of a design process? And how do the various design models score on these performance indicators, depending on context and nature of the design task? It should be these differences in expected performance that should guide the choice of a prescriptive design model. But these performance indicators and the scores of design models on these indicators are seldom spelled out in depth in the presentation of prescriptive design process models. The main (implicit) performance indicator of such prescriptive design models may be that application of such models will make the process manageable or just that they will generate “a satisfactory design”, as in the quote given above.

2.3 design science and the science of design

For the clarification of the differences between descriptive and prescriptive (process) design models one can use the distinction Cross (1993) makes between two streams in design research, viz. *design science* and *the science of design.* The latter refers to empirical, descriptive research on the actual practice of design, aimed “to improve our understanding of design through ‘scientific’ (i.e. systematic, reliable) methods of investigation”. Design science, on the other hand, refers to “an explicitly organised, rational and wholly systematic approach to design”. Elsewhere he makes a similar distinction, writing about respectively “research *into* design” and “research *for* design” (Cross, 1995).

While both research streams are clearly recognizable in the publications in the various academic design journals, I would like to give a slightly different interpretation to the concept of design science by putting the distinction of Cross in the perspective of other academic disciplines. One can make a general distinction between “*explanatory sciences*” like physics and sociology, and “*design sciences*”, like medicine and engineering (Van Aken, 2004). The mission of an explanatory science is to describe, explain and predict, or in other words to understand. The mission of a design science, on the other hand, is to develop knowledge, which the professionals of that discipline can use to design solutions for the problems in their field. One may regard Cross’ science of design as an explanatory research stream, aiming at descriptive process models, describing and possibly explaining certain design processes one has in practice. And one may regard his design science as a design-oriented research stream; one could also say an “engineering-like” research stream, aiming at prescriptive process models. As will be discussed below, prescriptive process models can be seen as *solution concepts* to be used in process design. The approaches advocated in design science will often be “explicitly organised, rational and wholly systematic”, as Cross says, but not necessarily so. For instance, in radical design one might want to apply solution concepts to the design process in which design activities are rather loosely organized to promote creativity and serendipity.

For professional design a designer needs state-of-the-art design knowledge, which is the subject of the next section.

3. Design knowledge

In designing a senior designer uses his/her *repertoire of general design knowledge* (Schön, 1983). In this article I define design knowledge simply as knowledge that can be used to produce designs. The *general* design knowledge in the repertoire of the senior designer is compiled by him/her over the years through formal education and through learning on the job. Once a designer has got a specific design assignment he/she will start to collect *specific* design knowledge, to be used for this specific assignment. In this article we are primarily interested in the nature of the general design knowledge and in ways to develop such general design knowledge.

3.1 categories of general design knowledge

In line with the three types of designs, discussed in section 1, one can distinguish three categories of general design knowledge, i.e.

- *object knowledge*, knowledge on the characteristics and properties of artefacts and their materials
- *realization knowledge*, knowledge on the various physical processes to be used to realize designed artefacts
- *process knowledge*, knowledge about the characteristics and properties of design processes, which can be used to produce process-designs.

Object knowledge is called “substantive knowledge” by Bunge and process knowledge “operative knowledge” (Bunge, 1966). As is often done, no separate attention is given by him to realization knowledge, which is probably subsumed under substantive knowledge.

Design repertoires contain these three types of general design knowledge. Typically the repertoire of a designer consists predominantly of general object knowledge. It will also contain some working knowledge of the processes which will be used to realize their designs, in order to take these into account at object design – like in Design for Manufacturing - but detailed realization knowledge tends to be the domain of specialists in the field in question. And it may contain only a limited amount of *explicit* process knowledge. Most designers obtain their process knowledge in a craftsman-like manner, i.e. by their own experience and by copying their teachers and peers. Process-knowledge tends to remain largely tacit; often designers find it difficult to express their approach to design problems.

In each of these three categories mentioned above a designer has *tacit* knowledge and *codified* knowledge (Polanyi, 1966; Nonaka and Takeuchi, 1995) and with respect to the codified knowledge one may make a further distinction between *experience-based* codified design knowledge, developed on the basis of an abstraction of the experience of one or more designers (like the VDI 2221 model) and *evidence-based* codified knowledge, based on formal systematic research.

And finally one has the distinction between descriptive and prescriptive design knowledge, to be elaborated in the next section. In this article we are primarily interested in *general prescriptive, evidence-based process design knowledge.*

3.2 prescriptive design knowledge

In order to analyse the nature of prescriptive knowledge I will use Bunge's philosophy of technology and, more specifically, his concept of *technological rule*. He defines a technological rule as "an instruction to perform a finite number of acts in a given order and with a given aim" (Bunge, 1967,p132). Prescriptive knowledge, then, should be based on the *logic* of the technological rule. This logic is: "if you want to achieve Y in setting Z, then do X". The core of the technological rule is this X, a general *solution concept* for a type of field problem. The remainder of the rule is a kind of user instruction for the solution concept, connecting it to the type of field problem, including indications and contra-indications for its use. Technological rules do not have to be formulated in the format given above. That format is only given to describe the *intervention-outcome logic* of the rule. The actual description of a rule may e.g. be a report or a set of drawings with explanation.

Technological rules are as old as modern man. Knowledge on artefacts like hand-held rock tools, dwellings and farm carts can, together with possible verbal explanations, be seen as technological rules, passed on to next generations to facilitate the making of similar artefacts. The work of Vitruvius contains many early technological rules on building. Over the centuries architecture and engineering developed further powerful technological rules on subjects like buildings, bridges, ships, fortifications, fire arms and machinery. However, with the scientization of building and engineering after the Enlightenment, an even more powerful variety came available, the *field-tested and grounded technological rule*. Using the methods of the natural sciences technological rules were *tested* in their intended field of application and knowledge on the mechanisms that determined their performance was *grounded* on the insights of those sciences (as well as on insights developed by the engineering sciences themselves).

Following Bunge, prescriptive design knowledge should use the logic of the technological rule: if you want to achieve Y in setting Z, then do (something like) X. And the most powerful variety of prescriptive design knowledge is the field-tested and grounded one. In each of the three categories object, realization and process knowledge, prescriptive knowledge should follow this intervention-outcome logic. When this reasoning is applied to design models one gets the following demands: if the model is to be a prescriptive one, it should be well documented what it is, especially the solution concept, the core of the rule (the

“X” in the logic of the rule; nothing new here), it should specify its application domain (the “Z “; this is not always done, implying that the design model is universal) and it should specify its expected performance (the “Y“, which isn’t always done either as we have seen). And in the more powerful variety of prescriptive design models, it is field-tested and it is known why it produces the desired performance.

Using a distinction made by Roozenburg and Eekels (1995) one can have *algorithmic* technological rules, which in principle *guarantee* the finding of a solution (do X, and you always have the solution). And one can have *heuristic* technological rules, which say “if you want to achieve Y in setting Z, then do something like X”. A heuristic rule does not guarantee a solution, but facilitates its finding. An algorithmic technological rule can be used as an *instruction* to be followed more or less unquestionably, without much understanding of its background and working mechanisms. However, a heuristic one is not an instruction but has to be used as a *design exemplar*, a general starting point for the design of a *specific* solution for a *specific* problem in a *specific* setting. This implies a *redesign from the general to the specific* and that needs considerable competence (Van Aken, 2004): a sound general understanding of the field in question (including knowledge of alternative technological rules which might be used for this problem), a thorough understanding of the rule itself and of the generating mechanisms producing its outcomes, and an intimate knowledge of the specific problem at hand: heuristic technological rules are not developed for the layman but for professionals in the field in question.

3.3 other sources of process-design knowledge

Of course the prime source of general process-design knowledge is the design literature. However, there are also various other bodies of literature from which one may get relevant process-design knowledge (see e.g. Schregenberger, 1998). These include the organization design literature, discussing the structuring of (usually) routine work processes which has similarities with the structuring of design processes (especially in the case of large in-house design processes). Also the discussion of planned organizational change can be relevant for process design as the introduction of new design processes has similarities with planned organizational change.

Another relevant body of literature is of course the project management literature. Design projects have much in common with other types of projects and several techniques from project management can also be used to plan and manage design projects, as we will see.

4 Designing design processes

As said, planning and organizing a design process can be seen as making a process-design. I will now discuss the nature of a process-design, in the subsequent section how that process-design may be made and then how it is to be realized in practice.

4.1 *design, designing and the principle of minimal specification*

In order to prepare the discussion on process design I will now give a working definition of the noun "design" and of the verb "designing". The literature gives many other useful definitions; the ones given here are chosen because they are helpful in the following discussion.

A *design* can be defined as a *model of an entity to be realised, as an instruction for the next step in the creation process*. That entity can be an object or a process. The model can take various forms, like a drawing, a text, a flowchart, a scale model, a computer 3D-representation, etc. A design is not an end in itself, but an input for the next step, which can consist of further detailing of the design in the world of designing or of the actual realisation of the entity in the material world. A model is an abstraction of reality. Usually it is an abstraction of an already existing reality, but in case of a design it is a model of a possible future reality.

Compared to the model, the physical object or process – the existing reality or the realised design - has innumerable *hidden properties,* properties that are present in reality but remain invisible in the model[2]. This brings us to the *principle of minimal specification:* a completed design should only specify what the makers of the artefact need to realize that artefact. Designing is producing information on a need-to-know basis. For instance, a design of a machine may not specify the colour of the housing of that machine. Either because the designer feels that that is unimportant (so the people of the workshop may choose a colour), or because the company in question has a standard policy on the colour of the housing. If the designer wants to deviate from that policy or feels that it *is* important, the colour of the housing of the machine will not be outside but inside the boundaries of minimal specification.

Designing can also be seen as a process of consecutive detailing, from a rough sketch, via an outline design to detailed designs. So the principle of minimal specification not only applies to the transition from designing to realizing, but also to the various steps within the design process.

For the design of material artefacts this principle of minimal specification is not very important: in practice designers learn fast not to under specify their designs and over specification usually doesn't do much harm. However, as we will see, for process design it *is* important.

The entity to be designed has to fulfil a certain function for the user. *Designing* can be defined as making a design. A more specific definition is "*designing is the process of determining the required function of an object to be designed, combined with making a model of it".* One can also say that designing is developing a *functional specification* of the object to be designed, combined with making a *technical specification* of it, i.e. a specification of the object in such a way that the makers of the object will have sufficient technical information to produce it.

The definition is specific, among other things because the process of making the functional specification is regarded as being part of the design process and not as being input to it. The reason for this is, that in general the designers have more design knowledge and more insight in the technical aspects of designing and realising the new object than the principals and other stakeholders in the design process and that in organising and planning the design process one should give much attention to the interactions between designers and these stakeholders (interactions, that are not only important in the first steps of the design process, but all along the whole design process). And for process design this inclusion of the development of functional specifications is even more important as those specifications tend to remain implicit. So it is up to the process designer to uncover the requirements of the various stakeholders on the design-process to be designed.

4.2 the process-design

A process design specifies the various activities of the design-process to be realized and their timing, plus a specification of the various actors that have to execute these design activities[3]. So a full process-design consists of two, strongly intertwined parts: a *process-structure* and a *role structure*. The process-structure is the planning part and specifies the various steps or sub processes of the design process and their sequence and timing. The role structure is the organizing part and specifies the actors and their roles in the design process. Combining the two should make clear for each step which groups or individuals have to perform that step. It is like the script of a play, which specifies on the one hand the various (speech) acts of the play (its process-structure) and on the other the dramatis personae, who have to perform the various (speech) acts: names, sex, age, general character and relations with the other persons (the role structure). Similarly, the role structure of a process-design not only specifies the various roles, but also their competencies, their authorities and responsibilities in the design process, and their relations with the other roles in the design process. Usually design models only specify the process structure and not the role structure (see e.g. the models of section 2.1). For individual or small-scale design processes this is understandable: filling in the role structure is fairly trivial. For large-scale design processes, however, the role structure should be a key part of the process-design.

The function of a process-design is to structure the design process to allow for subsequent management of this process and for coordination between the various parties involved in it. It is a means to analyse the design task, to design an action system that should be able to carry out this task effectively and efficiently and a means to inform all participants in the process on the nature, size, timing and mutual dependencies of their expected contribution.

The process structure of a process-design specifies in principle the *undisturbed process.* It is a model of what will happen if all goes according to plan. Of course, this never happens. So, the complement to the process-design is effective *process management* to carry the plan through and to handle in a kind of management-by-exception the consequences of the inevitable disturbances, like delays in finding solutions to certain design problems or changes in the functional specifications because the outside world will not stand still during the design process. Process management performs a function in a designed design-process like a director does in a play. Process management is a *function* at the level of the design project as a whole, but its role structure may be – and often is – distributed. In that case it is performed by one ore more central project planners or coordinators as well as by the individual designers themselves (distributed process management, of course, creates a coordination problem, but one that should be solvable).

The process-design specifies the undisturbed process, and especially its timing relations only in limited detail. It specifies the various process steps or stages, but usually not the timing of the basic activities of designing itself, like (using the model of Roozenburg and Eekels, 1994) analysis, synthesis, simulation and evaluation and the *iterations* (going back to previous activities) and *explorations* (doing preliminary work on subsequent activities) between these basic activities. Usually these iterations and explorations are scheduled by the designers themselves in dependence on the progress on the design task. But also with respect to the larger process steps process management may decide to schedule some unplanned iterations and explorations, depending on the progress of the design project. In repetitive, low-uncertainty processes there usually is much potential for improvement by separating planning and execution. In processes with more uncertainty like design processes, this potential is much lower. Instead one should put more effort in role definitions, leaving the actual scheduling of activities to the individuals and groups assigned to these roles themselves.

So the interpretation of a process-design for a design process has to be different from the interpretation of a model of a material process or a flow diagram of a software programme. The latter two specify exactly – to the detail chosen for the model – the timing relations between the various process steps, whereas the design process-design gives insight in the overall structure of the future design process and a broad outline of the timing relations, but the exact scheduling of these steps may be left to process management.

4.3 designing a process-design

Every formal design process has a *front end* in which that design process is prepared, see fig 2. The output of this front end is a *project brief*, giving the functional specifications of the entity to be designed, a justification for starting the design process (in New Product Development often in the form of a business plan), a definition of the resources to be involved in the design process and their funding and a process-design, specifying the process structure and the role structure for the design process. All these elements may be given in formal documents, but – depending on context and scale – there may also be only preliminary documents or even only implicit agreements.

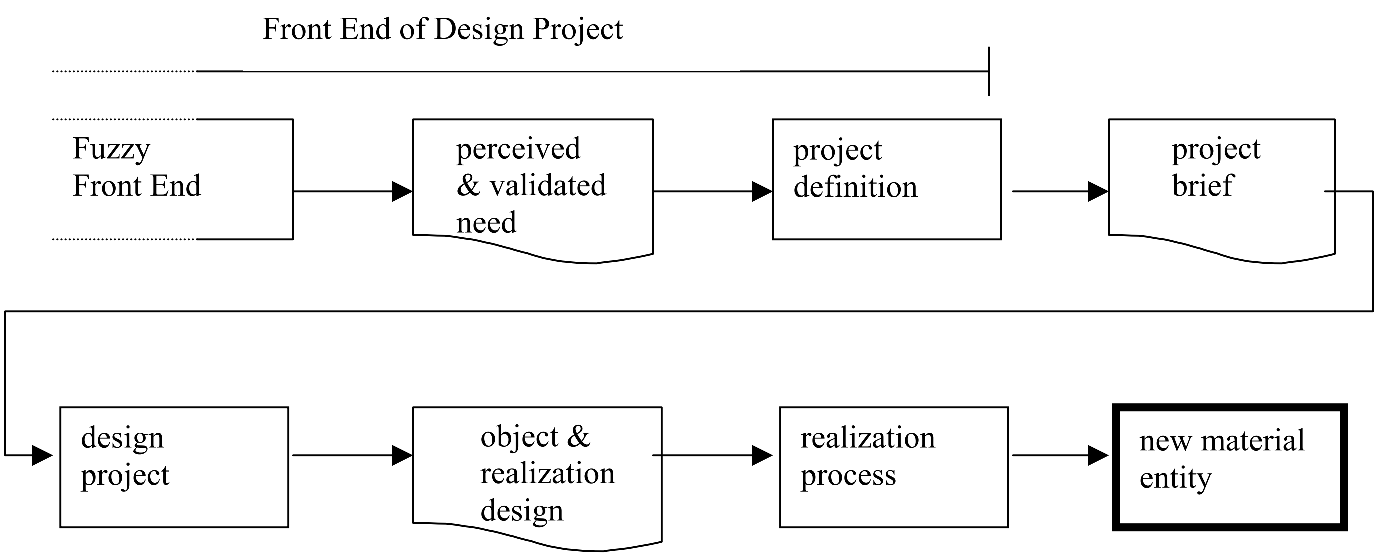

Fig 2. The Front End of a design project

Usually the first part of this front end is fuzzy, because participants may enter and leave the process at unpredictable times, while their ideas, interests (material and immaterial) and initiatives remain for quite some time undefined or underdeveloped (see e.g. Rubenstein, 1994, and Khurana and Rosenthal, 1997, on the concept of the fuzzy front end in New Product Development). This fuzzy front end results in the start of a formal design process if a *sufficiently powerful coalition of mobilizers* comes into being, which defines – possibly on the basis of some feasibility studies – a *perceived and justified need* for a new artefact. A coalition of mobilizers is seen as “sufficiently powerful” if they are able – or are expected to be able – to mobilize the resources needed for the design and realization of the artefact. The term “perceived” is used, because it is not the need itself that is input for the design process, but its perception by the mobilizers and because usually much further analysis and maybe interaction with the principal and the prospective users is needed to get further insight in this need. And the term “justified” is used to indicate that the need is seen as sufficiently worthwhile to invest the required resources to design and realize the entity in question.

Once the sufficiently powerful coalition of mobilizers has defined (more or less clearly) the perceived and validated need, the fuzzy part of the front end of the design process can be regarded as ended and the *project defining part* of this front end can start to produce the above mentioned project brief. It is largely in this planning part of the front end that the process-design is made. One can also do some process design for the planning part of the front end itself, and even some for the fuzzy front end, but this article deals with the formal process design in the project defining part of the front end of a formal design process. The resulting process-design is, however, not necessarily the final version; it may be adapted or further developed during the execution of the design project where and when deemed desirable.

Like in object design, professional process design involves a thorough analysis of the context of the process-design, its functional specifications, the use of state-of-the-art design knowledge and competent process designers. The analysis of the context of the design process includes a analysis of the various parties involved in the process, like the principal(s), other stakeholders, the designing parties (within an organization which departments and in a multi-party design process which companies and possibly individuals) and their competences. And maybe also an analysis of the risks in their participation, including possible risks in the funding of the project.

Like in object design professional process design needs functional specifications in order to make a good design. Such specifications – the requirements the design project has to fulfil – may be quite similar to the requirements other types of projects have to meet, which are “completion on time, within budget and to quality” (Turner, 2000). However, specific requirements are often largely implicit and have in that case to be elicited by the process designer from the various stakeholders in the design project. Especially the criterion “quality” is an elusive one in design projects and needs much attention.

In order to design a design process which is sufficiently manageable, adaptable and robust to meet requirements in time, cost and quality, the professional process designer needs state-of-the-art process knowledge, preferably including field-tested and grounded solution concepts. The use of such solution concepts means that process design becomes variant design. The process designer can choose from a range of solution concepts the one that fits best the requirements of his/her design project. Solution concepts can be used both with respect to the overall approach to the project as to various sub processes or structures, like the determination of the functional requirements for the entity to be designed or the roles and contracts of the various parties in the design project. So, he/she needs to know the expected performance of each of these solution concepts, depending on the context and nature of the design task.

In using variant design the process designer follows an approach similar to the common approach to object design, see e.g. the VDI 2221 model mentioned in section 2.1, where the choice of solution concept (for the object-design) is one of the key steps in the design process. Variant design means a *redesign* of the general solution concept to the specific situation and this needs – as said above – considerable expertise from the part of the designer. So the solution concept is not used as part of an *algorithmic* technological rule to be followed as an instruction, but as part of a *heuristic* technological rule to be used as a well-documented and well-understood design exemplar to be redesigned for the specific situation. As we will see, the realization of a process design involves a *second* redesign.

4.4 realizing a process-design

This article is written on the basis of the idea that object and realization design approaches and concepts can also be applied to design-process design. Designing involves the making a model of a to be realized structure or process. A model of a design process is in principle quite similar to a model of any other process, like e.g. a fully automated production process, involving robots. Both specify in more or less detail the various process steps or sub processes and the timing relations between them, be it linear sequences, iterations or other. The fundamental difference is not the design, but the realization of the design-process.

A realized object-design is a material artefact, made by makers – like building contractors or workshops – through material processes. A realized realization design – a building process or manufacturing process – is essentially a material process, driven by or supported by a human action system. A design process, on the other hand, is essentially a human action system, possibly supported by more material means like a CAD-system or a project web site.

The material process of the automated factory, mentioned above, is realized by factory engineers, mechanics and suppliers of robots and other equipment on the basis of a design of that process. This design specifies the nature of the various process steps and the equipment used in it, and predetermines the timing of these process steps, unconditionally or conditionally. In the latter case there are at some points in the process predetermined choices with respect to the next steps, to be made on the basis of predetermined conditions. The realization of the design of a material process typically gets only very limited realization freedom. And the execution of a material process is almost fully determined by its design and the material components of the process.

A human action system, on the other hand, is driven by the thoughts and feelings of the actors in question. These can be influenced by a design of that human action system, but are not determined by it. A design for a human action system – like a design process - is not made for robots but for individuals and groups with expertise and with self organization and self control faculties. Like designing itself, the realization of a process-design takes place in the immaterial world of texts and thoughts and is hardly constrained by fixed material conditions. A process-design for a design-process is realized through the *internalization* of the overall process-design by the designers in question and by a subsequent *redesign* by them of this overall design to a design of their own detailed activities (the *second redesign,* mentioned above). They have to learn the contents of the process-design and they have to be motivated to design and manage their own activities according to it. That internalization and redesign process is guided by verbal and written texts, flow charts, organization schemes and the like, but not determined by those. Designers usually take and get quite some realization freedom in realising the process design. This applies especially to the timing decisions, which are fully predetermined in the case of the material process, but are in the case of the design process much more left to the (possibly distributed) process management. Hence the more elusive character of process-designs.

Following the principle of minimal specification, a process-design should only specify what the realizers of that design need to realize it. As said, a process design is not made for robots. So process designers should try not to over-specify but should make conscious use of the principle of minimal specification and leave room for the redesign by the designers in the process. One of the consequence of this redesign is that the design-process designers have much less control over the realization of their design than in object and realization design. This has advantages as well as disadvantages. The advantages include the fact that one does not have to design the design-process in much detail (as is necessary in the case of the robots in the production process). Many details can (and must) be left to the selforganization and selfcontrol of the people in the process. The disadvantages include the possibilities of unmanaged deviations from the process-design, which may lead to coordination and throughput time problems.

The realization of a process-design for a large and complex design process often takes place in the context of a large organization, both in the case of a large in-house design project and in the case of large organizations cooperating in a large multi-party design project. Usually such organizations have already some design process in place. If the new process-design is really new, its realization has also the character of planned organizational change. Such a change should not only be managed in the technical-economic domain, but also in the political and cultural domains (see the TPC-model of Tichy, 1983).

5. Developing evidence-based process-design knowledge

As in object design, a key enabler for professional process-design is evidence-based design knowledge. And an important category of such design knowledge is the field-tested and grounded solution concept. The process designer should be able to choose from a range of solution concepts the one (or combination) that fits best his/her specific requirements. This applies both for the overall approach to the design process as for certain subprocesses, like the process of managing changes in the functional requirements or for certain role structures, like various models for design team composition and leadership.

As we have seen, one can find quite a number of design models in the literature, but field-testing and grounding of design models is fairly rare. One approach to the development of solution concepts is the multiple case-study (see e.g. Van Aken, 2004). The solution concept is developed through a number of field cases on the basis of cross case analyses and induction and subsequently tested and refined in a kind of Action Research (see e.g. Eden and Huxham, 1996, and Reason and Bradbury, 2001, on Action Research) with at first the researcher(s) in a supporting and developing role and in a later stage by the designers themselves without support. The multiple case should not only give information on the performance of the applied solution concept (depending on the context and the nature of the design assignment), but also in the underlying mechanisms producing that performance, the grounding of the solution concept. In this way the research process will give insight in the indications and contra-indications of the solution concept and in its application domain.

Solution concepts can also be developed through *research synthesis* in which the results of a variety of field research projects are used to develop a broader range of solution concepts for a certain design process problem and with more evidence on their performance than an individual research project can produce. This approach is based on systematic review as developed in Medicine as part of the evidence-based medicine movement. See e.g. Pawson, 2002, and Petticrew, 2001, on the general idea of systematic review, and Tranfield, Denyer and Smart, 2003, for its application in the field of organization and management, a field closer to design-process design than Medicine. The ultimate goal might be to develop a source book of design knowledge for process design like Hütte (Czichos, 2000) is for Engineering.

6. Discussion

This article is based on two main ideas. The first one is to use object design approaches to develop a more professional approach to process design. Especially for large-scale complex design processes a sound process-design with its process structure and role structure can be an important contribution to the performance of the design process in question with respect to time, costs and quality. Nevertheless one should bear in mind the differences between the use of object (and realization) designs and the use of process-designs, the most important being the far greater realization freedom designers have in realizing the process design compared to the people realizing an object-design or a realization-design. And this applies especially to the timing of the various process steps: in a material process this timing is (unconditionally or conditionally) pre-determined, while in a design process the timing statements in the process-design should rather be regarded as a first approximation to the timing of process steps than as the final word on it (as is the case in processes designed for robots).

An eloquent opponent to the use of object design approaches to process design is Bucciarelli(1994, p 110-125). If a process-design is expected to be realized like an object design, I would fully agree: it is impossible nor desirable to design a design process as if it were to be realized exactly as designed like in a process for robots. However, if a process-design is interpreted as discussed above, much of Bucciarelli’s doubts might be removed.

The second idea is the use of evidence-based prescriptive process-design knowledge in the form of field-tested and grounded solution concepts to produce process-designs. And, connected with this, the idea of doing field-research to develop such solution concepts. This idea it quite in line with one of the main traditional objectives of design research, being to develop *design methods.* Nothing new here. But, also the development of design methods has important opponents. Cross (1993) cites the disenchantment of the pioneers in the design field Christopher Alexander and J. Christopher Jones, who were turned off – in the words of Jones – by “the continual attempt to fix the whole life into a logical framework” (Jones, 1977). In fact they fear what Jacques (1980,p x) calls “the repressive effects of method”. Such a view seems to be based on the (implicit) assumption that methods or solution concepts are to be seen as *instructions*, to be followed strictly. Indeed design methods are sometimes presented as such. Or, in the words of Cross cited in section 2.3, methods are presented to create “an explicitly organized, rational and wholly systematic approach to design”. However, the solution concepts for process design presented here, are to be used embedded in *heuristic* technological rules: the solution concept is a well-tested and well-understood starting point for the design of a specific variant of it for the specific problem at hand. Not an instruction to be followed unquestionably. And subsequently it is up to the process designer to what extent he/she will try to fix by his/her process-design the life of his/her designers into a wholly logical and systematic framework.

7. Conclusion

Professional design of design processes can strongly contribute to a better performance of design processes, especially as the scale and complexity and the various demands on these processes increase. Also individual or small team design processes may benefit from a more professional approach to process design. It seems to be worthwhile to do further experimentation in practice and further research in process design in order to support the emancipation of process design from traditional, evolutionary determined approaches and to foster the development of more professional approaches.

End notes

1. Unlike French, German and Dutch, English does not make a distinction between the noun “design” and the verb “design”. This can cause confusion in the present article. Therefore, in case of the noun I will use “object-design” or “process-design”, with a hyphen, and “object design” and “process design” without the hyphen in case of the verb.
2. This position is based on the epistemological starting points of *realism*, see e.g. Sayer, 1984, and Archer, 1995. I follow realism’s contention that there exists a real (material) world, independent from observers and their knowledge. We can develop knowledge of that real world through our senses, even though sensory experiences are concept-laden and are therefore no objective images of the external world. Designs are entities in the immaterial world of knowledge, made to enable the production of entities that have a desired performance in the material world.
3. There are also other terms for process-design, like Cross’ term “design strategy”: “A design strategy describes the general plan of action for a design project and the sequence of particular activities, which a design team expects to take to carry through the plan” (Cross, 1994, p165). As do many other authors, he does not discuss explicitly the actors, who have to perform these activities.

References

- Andreasen, M.M. (2001). ‘The contribution of design research to industry: reflections on 20 years of ICED conferences’. *International Conference on Engineering Design,* Glasgow, 2001
- Archer, L.B. (1984). ‘Systematic method for designing’. In Cross, N. (ed) *Developments in design methodology.* London: Wiley
- Archer, M.S. (1995). *Realist social theory: the morphogenetic approach.* Cambridge: Cambridge University Press.
- Asimow, M. (1962). *Introduction to design.* Englewood Cliffs: Prentice Hall
- Bucciarelli, L.L. (1994). *Designing Engineers*. Cambridge: MIT-Press
- Bunge, M. (1966). ‘Technology as applied science’. *Technology and Culture,* 7, p329-340
- Bunge, M. (1967). *Scientific Research II*: The Search for Truth. Berlin: Springer Verlag
- Czichos, H (ed) (2000). *Die Grundlagen der Ingenieurswissenschaften*. Berlin: Springer (31st edition)
- Cooper, R.G. (1990). Stage-Gate Systems: A New Tool for Managing New Products. *Business Horizons* 33, May-June, p 44-54
- Cooper, R.G. (1994).’Third Generation New Product Processes’. *Journal of Product Innovation Management*, 11, p 3-14
- Cross, N. (1991). *Engineering Design methods.* London: Wiley
- Cross, N. (1993).’Science and Design Methodology: a Review’. *Research in Engineering Design*, 5, p 63-69
- Cross, N. (1995). ‘Editorial’. *Design Studies,* 16, p 2-3
- Dorst, K. (1997). *Describing Design: A comparison of Paradigms*. Rotterdam: Vormgeving Rotterdam.
- Dym, C.L. (1994). *Engineering Design, a Synthesis of Views* .Cambridge: Cambridge University Press
- Eden, C. and Huxham, C. (1996). Action Research for the Study of Organizations, in Clegg, S.R., Hardy, C. and Nord, W.R. (eds). *Handbook of Organization Studies,* p 526-542. Sage, London.
- Evbuonwan, N.F.O., Sivaloganathan, S. and Jebb, A. (1996). ‘A survey of design philosophies, models, methods and systems’. *Proceedings Institute of Mechanical Engineers* 210, p 301-320
- French, M. (1971) *Conceptual Design for engineers.* London: the Design Council
- French, M. (1994). *Invention and Evolution Design in Nature and Engineering.* Cambridge: Cambridge University Press, 2nd edition
- Jaques, R. (1980). Introduction to Jacques, R. and Powell, J. (eds) *Design; Science; Method.*
- Jones, J.C. and Thornley, D.G. (1962). *Conference on design methods.* London: Pergamon Press
- Jones, J.C. (1977). *‘How my Thoughts About Design Methods Have Changed During the Years’*. *Design methods and Theories* 11, p 48-62

- Jones, J.C. (1980). Design methods, seeds of human futures. London: Wiley (second edition 1992)
- Khurana, A. and Rosenthal, S.R. (1997). Integrating the Fuzzy Frond End of New Product Development. *Sloan Management Review.* Winter, p 103-120
- Marples, D.L. (1960). *The decisions of engineering design.* London: The Institution of Engineering Designers.
- Nonaka, I. and Takeuchi, H. (1995). *The knowledge creating company: how Japanese companies create the dynamics of innovation*. Oxford: Oxford University Press
- Pahl, G. (1198). Historical Background and Selected Results of Interdisciplinary Research between the Universities of Bamberg, Darmstadt and Munich. In Frankenberger, E., Badke-Schaub, P. and Birkhofer, H. (eds) *Designers, the Key to Successful Product Development*. Berlin: Springer
- Pahl, G. and Beitz, W. (1984). *Engineering Design.* London: The Design Council (original German edition 1971)
- Pawson, R. (2002). 'Evidence and Policy and Naming and Shaming'. *Policy Studies,* 23(3/4), pp 211-230
- Petticrew, M. (2001). 'Systematic review from astronomy to zoology: myths and misconceptions'. *British Medical Journal,* 322, pp 98-101 (also available at http://www.bmj.com/cgi/content/full/322/7278/98)
- Polanyi, M.(1966). *The tacit dimension.* London: Routledge and Kegan Paul
- Prasad, B. (1997). *Concurrent Engineering Fundamentals*. Upper Saddle River: Prentice Hall.
- Reason, P. and Bradbury, eds (2001). *Handbook of Action Research: Participative Inquiry and Practice*. London: Sage.
- Reymen, I. (2001). *Improving design processes through structured reflection, a domain-independent approach*. Eindhoven University of Technology, doctoral dissertation
- Roozenburg, N.F.M. and Eekels, J. (1995). *Product design, Fundamentals and Methods.* Chichester: Wiley (original Dutch edition 1991)
- Rubenstein, A.H. (1994). At the front end of the R&D/Innovation process: idea development and entrepreneurship. *International Journal of Technology Management* 9, p 652 – 675
- Sayer, A. (1984) Method in social science: a realist approach. London: Hutchinson
- Schön, D.A. (1983). *The refective practitioner.* London, Sage
- Schregenberger, J.W.(1998). 'The further development of design methodologies'. In Frankenberger, E., Badke-Schaub, P. and Birkhofer, H. (eds) *Designers, the Key to Successful Product Development*. Berlin: Springer
- Tichy, N.M. (1983). *Managing Strategic Change: Technical, Political and Cultural Dynamics.* Chichester: Wiley
- Tranfield, D., Denyer, D. and Smart, P. (2003). 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review'. *British Journal of Management*, 14, p 207-222.

- Turner, J.R. (2000). Project success and strategy. In Turner, J.R. and Simister, S.J. *Gower Handbook of Project Management*. Abingdon: Gower., p77-87
- Van Aken, J.E. (2004). 'Management Research Based on the Paradigm of the Design Sciences: The Quest for Field-tested and Grounded Technological Rules'. *Journal of Management Studies* 41, p219-246
- Van Handenhove, E. and Trassaert, P. (1999). 'Design Knowledge and design skills'. In Lindeman, U. et al. (Eds) *Proceedings of the 12th International Conference on Engineering Design*. München: Technische Universität München ,p153-158.
- VDI (Verein Deutscher Ingenieure) (1987). *Systematic Approach to the Design Technical Systems and Products* VDI-Guidelines 2221, VDI-Verlag
- Watts, R.D. (1966). 'The elements of design'. In Gregory, S.A. (ed) *The design method.* London: Butterworth

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